Spin bosons and spin glasses
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Introduction

The last centuries showed the birth of, among others, statistical mechanics and quantum mechanics; theories which are the basic building bricks of today's physics. By now we are familiar with concepts like phase transitions, critical phenomena, or quantum coherence; and with quantities like the partition function or the density matrix. It is during the last two centuries that physicists realized that a complete description of reality is intractable from a mathematical point of view. Not only this, they realized that it was unnecessary, as is the case of statistical mechanics, or that it was impossible, as is the case for quantum mechanics. Indeed, the answer to problems in physics changed from a given deterministic solution to a solution in terms of averages, or a set of probabilities for each of the possible events. Commonly, full solutions, even in terms of averages, were not possible since the mathematics at disposal was not sufficient to tackle the forthcoming problems. Approximations were called for.

Presently theoretical physics is mainly based on approximations. We can only find approximate solutions, or at most, solutions valid in a restricted range of the parameters involved in the problem. In spite of that, these solutions can give us most of the needed information and understanding. Another successful approach is to use simplified models which, however, keep the key features of more complicated and more realistic ones. From these “toy models”, we can infer the behavior of realistic models, we can test general ideas like, for example, critical phenomena and universality. This approach is, in fact, followed in the first part of this thesis.

This theoretical development was followed, or even sometimes pushed, by experimental development. For instance, the range of temperatures of contemporary experiments is much larger than only a few decades ago. Quantum effects are at the moment seen in many laboratories in the world. Very low temperatures, approaching $T = 0$, are now accessible and controllable. Understanding the physics at such low temperatures is important and new problems and worries arose from that. New phases of matter were discovered, such as Bose-Einstein condensates. New phase transitions were found, which brought a better understanding of critical phenomena. In addition, a new type of transitions was proposed, quantum phase transitions. Because they occur strictly at $T = 0$, they are rarely observed directly, but their presence can be inferred indirectly since many effects in very low temperature physics arise from lying in the vicinity of a quantum critical point.

One of the most interesting features discovered in the last century, was the exis-
tence of spins. We describe spins in many different ways depending on the purpose and the situation. For instance, spins are responsible for magnetic effects. Many approximations were needed to understand their behavior. Often, in a magnet, details on the dynamics of each of the spins are not of leading importance. Furthermore, the crystalline structure can break the symmetries at disposal, leading then, in the case of spins 1/2, to Ising or XY spins. The interactions between each pair of spins throughout the lattice can sometimes be treated as classical, though their origin is purely quantum mechanical. In spite of all these approximations, the problems typically remain unsolvable. To overcome that, several approximations and generalizations in the algebra describing spins have been performed, during many years of study. A very successful generalization is the so-called spherical spin approximation, to which the first part of this thesis is devoted. A quantum spherical model is presented and solved there in order to study quantum phase transitions. This is one of the simplest models showing non-trivial critical phenomena. We will show how spherical spins can arise as a limit of Heisenberg spins and that leads to an analytically tractable problem. With this model we can analytically study critical phenomena of a quantum phase transition, i.e., we can calculate exactly the involved critical exponents, the critical amplitudes and the relation with the classical counterpart.

As technology improved, new ways to study spins appeared. Nowadays, for instance, it is common to deal with SQUIDs (superconducting quantum interference device) which can be understood as a two level system, thus analogous to a spin 1/2. In this situation, with only one SQUID, no spin-spin interaction is present but the dynamics play an important role. Furthermore, these types of systems cannot be isolated from the external world around them, therefore the interaction with the environment must be taken into account. Thus we jump from a static approach, i.e., in equilibrium, like the one we often have in magnetism, towards a dynamical one. Many other systems can be approached in this manner. In nuclear magnetic resonance (NMR), one deals with an ensemble of spins that can, sometimes, be considered as non-interacting. There, by using very strong magnetic pulses, it is possible to tune the dynamics of the spin up to the point to be able to perform controlled rotations on the Bloch sphere. Experimentally the dynamics is analyzed in free induction decays (FID). The environment also plays an important role here. The dynamics of the system is biased by the surroundings of the sample, bringing decoherence and damping. This is the subject of part II (chapters 3 to 6) of this thesis. In this part, an exactly solvable limit of the spin-boson model is presented and solved. The model is a description of the dynamics of an ensemble of spins on which NMR pulses are applied. As in the previous part, the approximations are performed when posing the problem, and not “half way” as is most frequently done. This reduces its applicability but in exchange, it leads to an analytically solvable model. The first objective of this part is to use this model to study new mechanisms of work extraction, for instance lasing, in such microscopic systems. These techniques are expected to have a number of advantages over the standard ones. The second objective is to cool spins, i.e., to obtain purer spin states, since the efficiency of, e.g., NMR studies depends strongly on the initial polarization of
the spins. Enhancing that quantity enhances the output signal in the experiment. The problem of cooling is well-known. However, some important objectives are not yet met with the existing methods. This led us to propose a new method of cooling, where the bath is involved in an essential manner.

Advances in the fields of chemistry and physics of materials allowed precision creating new materials. For instance, creating alloys of different metals at a given precise concentration of their constituents. Examples of that are for instance $\text{Au}_{1-c}\text{Fe}_c$, a transition metal embedded in a noble metal, which for certain concentrations $c$ is a spin glass. The discovery of spin glasses boosted an at that time young branch of statistical mechanics, the study of disordered systems. Indeed, spin glasses can be understood as disordered magnets which at low temperatures condense in a frozen disordered configuration instead of a periodic one.

Part III (chapters 7 to 9) is focused on spin glasses. In this part our aim is more modest than to start from a simplified Hamiltonian and evolve analytically till the end. In chapter 8 departing from the fact that at finite temperature the range of the RKKY interaction is cut-off, we give a description of the dependence of the transition temperature on the concentration of magnetic impurities in metallic spin glasses.

In chapter 9, finally, another way to tackle intractable problems is considered, namely computer simulations. With the help of computers, simulations of unsolvable models can be carried out and important results can be found. This brings a whole new dimension to physics, since the problems are no longer the unsolvability but, for instance, the too small size of the simulated systems that has to be chosen, because a computer has finite memory and limited speed. In chapter 9 a numerical simulation of a spin glass on a hypercubic cell is presented. With this simulation we study how this finite size and finite connectivity model approaches the well known infinite size, infinitely connected mean field model of the spin glasses.